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The Collection of The Main Issues for Wind Farm Optimisation in Complex Terrain

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Abstract: The paper aims at establishing the collection of the main issues for wind farm optimisation in complex terrain. To make wind farm cost effective, this paper briefly analyses the main factors influencing wind farm design in complex terrain and sets up a series of mathematical model that includes micro-siting, collector circuits, access roads design for optimization problems. The paper relies on the existing one year wind data in the wind farm area and uses genetic algorithm to optimize the micro-siting problem. After optimization of the turbine layout, single-source shortest path algorithm and minimum spanning tree algorithm are used to optimize collector circuits and access roads. The obtained results can provide important guidance for wind farms construction.

1. Introduction

Micro-siting is an important step in the exploitation and utilization of wind power, especially in complex terrain, i.e. mountainous regions. Since the terrain undulates greatly, the wind energy distribution is affected by many factors, which make it very difficult to select microscopic locations for wind farms in complex terrain [1].

The tortuous path of collector circuits and the number of branch lines are influenced by the layout of wind turbines. For a 2MW wind turbine, its outlet voltage is 35kV after a box-type transformer and finally gets into a step-up substation through collector circuits [2]. Depending on the arrangement of wind turbines, the number of the main circuits determines the length of its path and the size of conductor cross-section, and thus influences the total investment of the project.

An appropriate design of overhaul road is significant to the investment and operation of a wind farm. The design of ooverhaul road is straightforward for wind farms in grassland, desert or coastal areas, but it is an important part for wind farms in mountainous regions, such as most inland wind farms in China. However, there is a lack of the study on access road selection, and many enterprises often design it according to their experience. Because of the huge amount of work and low efficiency, no guarantee exists in its optimization.

In this paper, we consider the microscopic locations selection problem for erecting wind farms in complex terrain by taking power output, collector circuits and access roads into account.

2. Integration Optimum Design for a Wind Farm in Complex Terrain

While designing a wind farm in complex terrain, one could have a preliminary determination of turbines' sites by optimizing its power output. But the final determination shouldn't be made until taking collector circuits and access roads all into consideration. Therefore, this paper puts forward a further program to optimize collector circuits and access roads based on micro-siting optimization.

2.1 Micro-siting Optimization Design

This paper focuses on how to micro-site turbines in mountainous regions, according to wind resource distribution, topographical features, turbine's parameters, and etc. For a complex terrain without apparent wind direction, it is impossible to site turbines empirically. Instead algorithms and strategies are preferable to optimize turbines' layout [3]. This paper uses genetic algorithm to optimize turbines' layout in order to maximize annual power output and minimize wake loss in a given area.

Considering the case of wind that blows from all directions with different speeds[4], the wind directions are then divided into 12 (or other value) intervals where the 1st interval is for north wind and the next interval is obtained by 30 degree clockwise rotation of the former one. The wind speeds in all the directions at every point in the wind farm are obtained from the simulation of wind resource [5]. Wind speed distribution is described the wind speed probability distribution function of time, the probability density. There are many mathematical functions which are used to describe the probability density distribution; Weibull distribution and Rayleigh distribution are commonly used. Weibull distribution curve has two parameters: the shape parameter k and scale parameter c characterization, shape and scale parameters are all positive. The shape parameter k decided distribution range, scale parameter c decide the position of maximum points. Using Weibull distribution to describe the average wind speed changes, the average wind speed probability density function can be expressed as:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp^{-(v/c)^k} \tag{1}$$

The cumulative distribution function of the average wind speed can be represented as:

$$F(v) = 1 - \exp(\text{-}(v/\mathrm{c})^{\mathrm{k}}) \tag{2}$$

Optimization for wind farm micro-siting is a multi-variable nonlinear optimization problem. The optimization variables are the location coordinates of each wind turbine. While siting the turbines, wake effect should be taken into account. Wake models like Park, Jensen, Frandsen and Larsen, all well simulate the wake situation in flat terrain. Jensen model has been implemented in this paper. It assumes an initial velocity deficit immediately behind the turbine rotor, which is calculated from the turbine's thrust coefficient (Ct), and an empirically determined wake-decay constant, which sets the linear rate of expansion of the wake with distance downstream. It assumes that the wind flow, including the entrained wake, follows the terrain. The effects of multiple wakes are taken into account by superimposing, or overlapping, the wake cross sections of the upstream turbines. If a wind speed distribution table (TAB file) from a measurement mast is available and associated with the wind resource grid (WRG), the energy capture uses this table to determine the probabilities. The WRG is then used only to determine the average wind speeds at other locations relative to the mast location. The principal rationale for TAB files is that measured speed and direction distributions are usually more accurate than modeled distributions. In addition, TAB files provide a mechanism for "anchoring," or adjusting, the mean wind resource to measurements at one or more points, which can reduce the overall bias in the energy production estimate. For this method to work reliably, the TAB file must be associated with a single-point WRG. The single-point WRG represents the WRG interpolated exactly to the mast location. For each direction, the program finds the ratio of the average wind speed at other points in the WRG to that of the single-point WRG; these ratios are called speed-ups. The speed-ups are then used to adjust the wind resource at the turbine locations in the energy capture loop before being input into the power curve function. speed-ups for each direction step are calculated for each turbine at its current location using the following relationship:

$$su_{xy\alpha} = \frac{u_{xy\alpha}}{u_{m\alpha}} \tag{3}$$

where $su_{xy\alpha}$ is the speed up at location (x,y) for direction step α, $u_{xy\alpha}$ is the mean wind speed from the WRG at location (x,y) and for direction stepα, and $u_{m\alpha}$ is the mean wind speed at the mast for the same direction step α from the single-point WRG.

According to the size of the overlap made by the upwind turbine, the ratio of the distance between the two turbines and the turbine radius, and their altitude, the incident wind speed at a downwind turbine can be worked out. Furthermore, the effect on the output power can be known under ideal circumstances. To prevent the distance between the turbines from being too close, the location coordinates ought to meet the conditions of both boundary and distance constraints simultaneously. Supposing that the minimum distance between two turbines is L, the constraints for turbines are shown below:

$$\begin{cases} \left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2 \geq L \\ \quad x_{\min} \leq x_i \leq x_{\max} \qquad i \neq j \ \ i,\ j \in N \\ \quad y_{\min} \leq y_i \leq y_{\max} \end{cases} \tag{4}$$

where (x_i, y_i) is location coordinates of turbine i , N is the amount of turbines, x_{min}, x_{max}, $y_{min}$and y_{max} are the lower and upper limits of both lateral and horizontal location coordinates, respectively. Moreover, the amount of the turbines and allowable slope are also constraints.

The objective function is defined as:

$$E = \max\left(\sum_{j=1}^{N} E_j\right) \tag{5}$$

Where E_j is the annual power output of turbine j after taking wake effect into account. According to the steps of genetic algorithm [6], the initial population is generated randomly. The genetic algorithm for real number coding is used in Matlab, the number of iterations for 3000 times and the specific steps are illustrated in Fig 1 below.

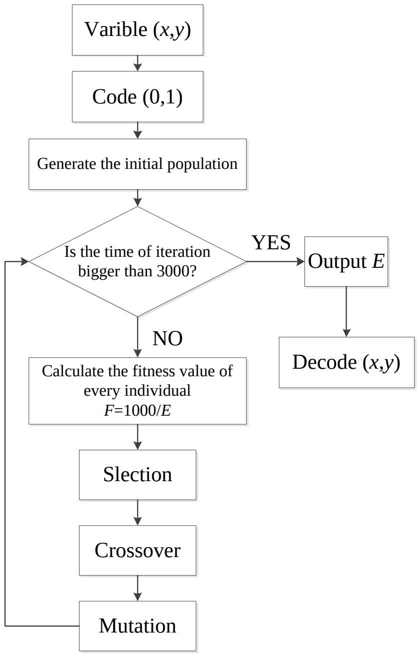

Fig 1 Flow Chart of Genetic Algorithm

2.2 Collector Circuits Optimization Design

If a wind farm locates in a complex terrain like a mountainous region, then its collector circuits are often dealt with as buried cables so as to reduce the environmental impact. The voltage is boosted to 35kV through a box-type transformer, then, looped the copper bus of the higher side of the transformer and finally sent it to the booster station [7]. The number of the collector circuits is determined by the grouping of turbines, which follows the principle of equal distribution to an extent. But considering the influence of actual terrain, the maximum output capacity of each circuit should be ensured to meet the limit of a single circuit transmission capacity.

In this section, the optimization variable is the distance between two wind turbines. It isn't just a straight line distance in a complex terrain, but is calculated by an algorithm called Dijkstra, which is used to find the single-source shortest path. The single-source shortest path problem, as illustrated by Fig 2 below, where the vertices represent the location of fans and the points mean grid nodes, is to seek the turbine that has the shortest path from it to any other ones in the map given. The path is regarded as the weight of the spanning tree.

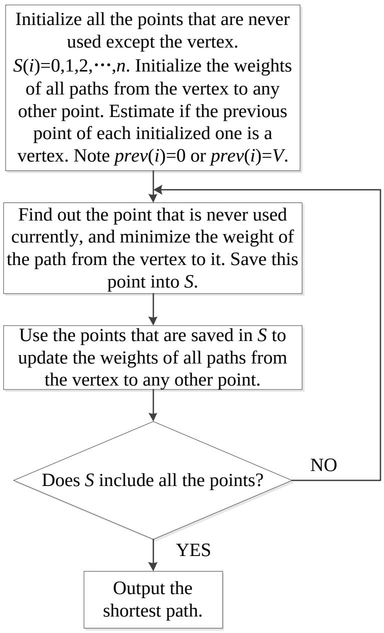

Fig 2 Flow Chart of Dijkstra Algorithm

On the other hand, selecting the cross-section of the cable should be done according to the topographic map with sensitive areas and turbine sites, the coordinates of the booster station, and the number of the collector circuits. Thus some requirements are needed: 1) Larger than thermally stable minimum cross-section; 2) Voltage loss is less than the set value; 3) Bending radius is 15 times bigger than its diameter. Besides, collector circuits are considered to connect in single return type, and not to cross each other. The cost of cable accounts for about 10% of the whole project cost of investment, so under the condition of mature technology to the same circuit, it is necessary that different economic capacity and section is piecewise chosen. Generally in the whole project it is advisable to choose up to three types of cable, too much cable model can increase the difficulty of construction projects, also bring inconvenience of the late operation maintenance. Therefore, the cross-section of a long cable (longer than the maximum disc length of manufacturers' production), should generally less than 300mm^2 and a transition joint is needed in that case.

In this section, the optimization object is minimize cost, the cost is calculated as:

$$C = l_1 \cdot C_1 + l_2 \cdot C_2 + \cdots + l_n \cdot C_n \tag{6}$$

where C_1~C_n are the cost per unit length of the collector circuits (by ￥ten thousand/km), determined by the conductor material and cross section， l_1~l_n are the length of each section (by km).

An improved Minimum-Cost Spanning Tree algorithm (MCST) for optimal planning of connect collector circuits. Some concepts are defined: The fans and booster station are regarded as a figure of vertexes. The routes, along which, feeder lines might be implanted are regarded as edges. The cost of each feeder is defined as the weight of the corresponding edge. Based on the preliminary planning results of basic minimum-cost spanning tree algorithm, Under the premise of meeting voltage drop and correct current carrying capacity, calculate the appropriate cable cross-section by using economic current density. By adjusting the weights of each edges dynamically and implanting an iteration method, the optimal planning result of the minimum total cost is obtained.

2.3 Access Roads Optimization Design

Access roads optimization is performed based on the minimum access roads cost as the objective function [8]. Therefore, in this section, the optimization parameters consist of two aspects: 1) The layer material cost of road structure; 2) The earthwork cost. The former, can be divided into the volume and its unit price. So the formula is implemented as:

$$M_c = H \cdot L \cdot W \cdot M_P \tag{7}$$

Where M_c is the total cost of the layer material, H is its thickness, L is the length of the road, W is the width of the road, and M_P is the unit price of the layer material. The latter also can be divided into the volume of earth and its unit price. Its calculation is divided into the following situations: 1) When road fill and road excavation achieve an overall balance, it is considered that only in the range of 1km earthwork can be allocated evenly, and the earthwork cost is equal to the amount of excavation multiplied by the unit price; 2)When road excavation is larger than road fill, the earthwork cost, which is calculated according to the excavation, is equal to the amount of excavation multiplied by the unit price that includes the spoil cost; 3)When road fill is larger than road excavation, the earthwork cost is equal to the difference between fill and excavation multiplied by the unit price of road fill, and then add the amount of excavation multiplied by its unit price:

$$\begin{aligned} E_C &= V_C \cdot C_p & (V_C \geq V_F) \\ E_C &= (V_F - V_C) \cdot F_P + V_C \cdot C_p & (V_C < V_F) \end{aligned} \tag{8}$$

Here E_C is the earthwork cost, V_C is the amount of excavation, V_F is the amount of fill, C_P is the unit price of excavation, and F_P is the unit price of fill. There are many method to calculate earthwork, such as grid method, triangulation method and section method. And in practical engineering, according to the characteristics of the road engineering, cross section method is used to approximate calculate earthwork. It is not only adapted to the planar terrain, but also adapted to the ribbon terrain and topography. After the section is generated, design line is drawn in accordance with the requirements of design, the area surrounded by the measured line and design line is calculated, as shown in the figure3 below. Then the average area of the adjacent two sections and the spacing between adjacent two cross sections can be calculated, so the volume between two adjacent sections and each section of the adjacent additive volume can be calculated. Finally it is concluded that the total earthwork.

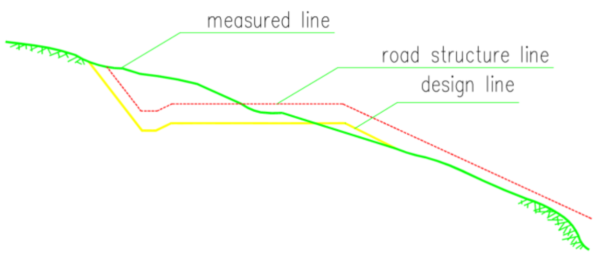

Fig 3 Road longitudinal profile

Some constraints should be satisfied in the process of optimization: 1) The access roads design level. Access roads should be designed as the 4th level road for factories and mines, i.e., their minimum curvature radius is 15m, minimum vertical curvature radius is 100m, and minimum vertical curve is 20m. 2) Longitudinal slope restrictions. In mountainous or hilly regions where engineering projects are so arduous, it is generally required that the slope should not be larger than 10%. 3) Land restrictions in the farm. Usually, a wind farm is relatively large in size, within its range, there may be a farmland, forest land, etc. Hence, optimization selection should try to avoid them according to actual conditions. 4) Surface feature restrictions in the farm. These surface features include cultural relics and historic sites, tombs, villages and so on. Optimization selection should try to avoid them depending on real situations. Road edge avoidance should meet certain requirements for distance, and 100m is generally considered for that.

In this section, the objective function is the minimum cost of building access road:

$$OPT = \min\left(M_C + E_C\right) \tag{9}$$

Road design automatically optimizing and routing algorithm [9] in a wind farm is similar to the collector circuits' optimization. First the shortest distance between two wind turbines is worked out through the Dijkstra algorithm, then the amount of road excavation and road fill is calculated, next the cost is calculated according to Formula (8) and regarded as the weight of the tree. Finally, the plan is optimized by using minimum spanning tree algorithm.

3. Optimization Design Example

Based on the above-mentioned features on the collection of the main issues for wind farm optimisation in complex terrain and related technologies, the software for integrated optimization design of wind farm in complex terrain is developed, which can be used to optimize micro-siting, collector circuits and access roads simultaneously. In this section, taking a real wind farm as an example, this software is used to design and simulate the wind farm project.

3.1 Description of the Actual Wind Farm

This wind farm is in a complex terrain, and its topographic map is illustrated by Fig 4 below. Its *X* range (longitudinal) is between 712536~724156m, *Y* range (latitudinal) is between 4624300~4639110m, and its H range (altitudinal) is between 0~1580m. The wind measurement mast locates at (715828, 4631910). It is expected to put 33 wind turbines with 2MW rated power in the wind farm.

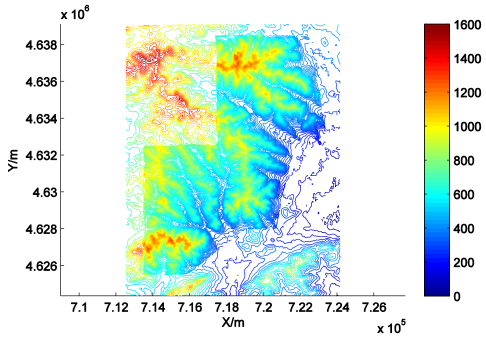

Fig 4 Wind Farm Topographic Map

The specific set parameters of the wind farm and wind turbines are given in Table 1.

Table 1 Parameters of Wind Farm and Wind Turbines

Parameter Name	**Value**
Wind Turbines' Minimum Spacing / m	320
Allowable Slope / °	10
Tower Height / m	60
Wind Shear Exponent	0.142857
Number of Wind Sectors	12
Number of Wind Speed Intervals	20
Rotor Diameter / m	84
Hub Height / m	70

Table 2 presents the parameters of collector circuits and cables. Copper is selected for conductor material, and dry loess is selected for laying soil. The booster station locates at (715828, 4631910), and the trench outside the booster station starts at (715800, 4631900).

Table 2 Parameters of Collector Circuits and Cables

Parameter Name	**Value**
Number of Circuits	3
Buried Depth / m	1
Power Factor	0.95
Thermally Stable Minimum Cross-section / mm	95
Maximum Voltage Drop / %	10
Single-disc Cable Length/m	800
Additional Cable Length/m	3000
Maximum Operating Temperature / ℃	90
Ambient Temperature / ℃	20
Thermal Resistivity/ (K.m^2/w)	1.2

The design parameters of access roads in the wind farm are shown in Table 3.

Table 3 Parameters of Access Roads

Parameter Name	**Value**
Pile Spacing / m	100
Allowable Slope / °	10
Sensitive Area Separation Distance / m	100
Road Width / m	5
Layer Thickness / m	0.2
Unit Price of the Layer Material / yuan	500
Unit Price of Road Excavation / yuan	5
Unit Price of Road Fill / yuan	4

3.2 Optimization Results

Using the integrated optimization algorithm, the calculations are performed. The result shows that the ideal annual energy production for this wind farm without considering wake loss is 292.431GWh. When the wake loss is considered, its power generation is 287.043GWh. What's more, the average wake loss will be just 1.823%. The optimized turbine sites situation is illustrated in Fig 5 below，green point represent turbines.

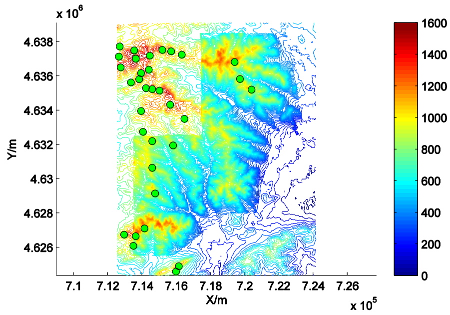

Fig 5 Optimal Turbine Coordinates Distribution

Turbines are distributed relatively evenly in order to have a much clear view on the layout of collector circuits and access roads. In this project, copper is selected as the cable material. According to the given information of different cable cross-sections, after optimization, the selected cables, which cost ￥28,839,240 in total, are 95mm, 120mm and 150mm in cross-section, and each extends 47.41km, 3.09km and 10.72km, respectively. The power loss at booster station is 757.35kW, and cable power loss is 7.75kW. Overall, the total loss is just about 0.01%.

The paths of collector circuits are illustrated in Fig 6. These collector circuits can be divided into 3 single loops, with 11 wind turbines connecting to each, and they are represented by red, yellow and green respectively.

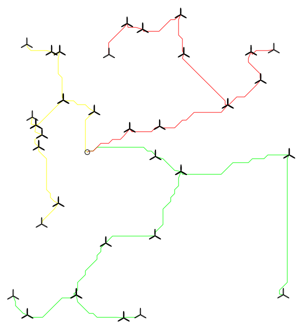

Fig 6 Path Diagram of Collector Circuits

Access roads are designed as illustrated in Fig 7. The blue lines represent the connection mode, while the red points represent pegs. By optimizing the road paths and routing reasonably, access roads, which cost ￥28,662,240 overall, are designed as 56km in length. The amount of road excavation is 74,244.35m^3, and the amount of road fill is 76,926.06m^3.

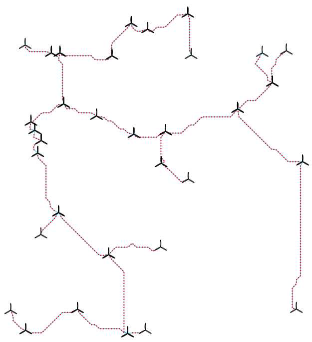

Fig 7 Layout Diagram of Access Roads

3.3 Results Analysis and Comparison

To validate the algorithm, the plan above is compared with the one formulated according to the traditional experience. The empirical rules for turbine layout are: 1) Wind turbine spacing along the main wind direction is 5~9 times the rotor diameter. 2) The spacing along the direction that is perpendicular to the main wind direction is 3~5 times the rotor diameter. 3) wind turbines is erected in the area where wind energy resource is relatively good, i.e., relatively higher areas [10], as illustrated in Fig 8. According to the calculation, the annual power generation of the experiential plan is 260.326GWh, which is 9.31% less than the optimized plan. By comparing the results, a conclusion could be drawn that the optimization method proposed in this paper could be applied to actual wind farm micro-siting.

Meanwhile, according to empirical rules, the cables of collector circuits cost is ￥32,008,670, which is 10.99% more than the optimized design. Also, the cost of access road building is ￥32,669,220, which is 13.98% more than the optimized design. By comparing the results, another conclusion could also be drawn that, compared to the empirical design, the optimized design for collector circuits and access roads can not only shorten the construction period, but also reduce the investment, which consequently could be better applied to practical engineering.

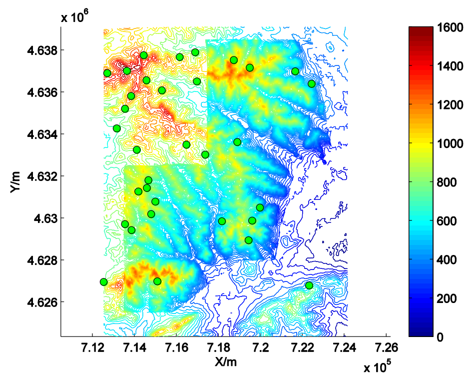

Fig 8 Turbine Coordinates Distribution determined by experience

4. Conclusion

Through the above analysis, some conclusions can be drawn as follows:

- In the micro-siting module, this paper uses a variety of wake models and topography effect models, which can predict the wake loss between different wind turbines in complex terrain. Probability density algorithm is used in power model, and by the discretization of wind speed and direction, the probability forecast could be more precise from the micro-aspect.
- This paper describes a whole set of design method to optimize collector circuits design, select cables and calculate cost reasonably, thereby further improves the security and reliability of collector circuits operation in wind farm.
- The algorithm that this paper has developed, should be launched at feasibility design phase, especially at micro-siting and access roads design phases. Under certain conditions when road connection is relatively difficult or road building investment is relatively large, it is necessary to change the turbine site even if this causes some power generation loss, in order to reduce the cost.
- Through comparison and analysis, this algorithm is proved to be feasible and advantageous, which can provide important guidance for engineering application.

Acknowledgments

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References

[1] Manwell, J. F, McGowan, J. G, Rogers, Anthony L. Wind Energy Explained: Theory, Design and Application, Second Edition[J]. Wind Engineering, 2006, 30(2):169-170.

[2] Banerjee Binayak， Islam Syed M. Reliability based optimum location of distributed generation[J]. Electrical Power and Energy Systems，2011，33(8) : 1470—1478..

[3] Castro Mora J, Calero Barón JM, Riquelme Santos JM, Burgos Payán M. An evolutive algorithm for wind farm optimal design. Neurocomputing 2007;70(16e18):2651-8.

[4] Andrew Kusiak，Zheng Haiyang，Song Zhe． Wind farm power prediction：A data-mining approach[J]． Wind Energy，2009，12(3)：275-293．

[5] Carta J A, Ramírez P, Velázquez S. A review of wind speed probability distributions used in wind energy analysis: Case studies in the Canary Islands[J]. Renewable & Sustainable Energy Reviews, 2009, 13(5):933-955.

[6] Saavedra-Moreno B, Salcedo-Sanzand S, Paniagua-Tineo A, Prieto L, PortillaFigueras A. Seeding evolutionary algorithms with heuristics for optimal wind turbines positioning in wind farms. Renewable Energy 2011;36(11):2838-44.

[7] Liu Yongqian，Shi Chenxing，Dong Cuiping，Han Shuang． Optimization of electricity collecting system for wind farm based on orthogonal experimental design[J]． Journal of solar energy，2013，12：2115-2120(in Chinese)．

[8] El-Masry M A, Nassar K, Osman H. Simulating the Effect of Access Road Route Selection on Wind Farm Construction[C] The 2011 ASCE International Workshop on Computing in Civil Engineering. 2011:3272 - 3282.

[9] Gonzalez-Longatt F M, Wall P, Regulski P, et al. Optimal Electric Network Design for a Large Offshore Wind Farm Based on a Modified Genetic Algorithm Approach[J]. Systems Journal IEEE, 2012, 6(1):164-172.
[10] Abbes M, Belhadj J. Wind resource estimation and wind park design in El-Kef region, Tunisia[J]. Energy, 2012, 40(1):348–357.